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THE RELATIONSHIP OF TEMPERATURE TO STRENGTH AND POWER PRODUCTION IN INTACT HUMAN SKELETAL MUSCLE

by

Richard William Cote III

A Dissertation Submitted to the Faculty of the

COMMITTEE ON ANIMAL PHYSIOLOGY (GRADUATE)

In Partial Fulfillment of the Requirements
For the Degree of

DOCTOR OF PHILOSOPHY

In the Graduate College

THE UNIVERSITY OF ARIZONA

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ABSTRACT

Eight male subjects volunteered to participate in a study to determine the relationship between variations in Tm and the characteristics of strength and power development in intact muscle. The subjects were studied under control and four experimental conditions, two active warm-up conditions (W-A and W-B) and two passive warm-up conditions (heating and cooling). Each subject was tested on the Cybex II isokinetic testing device at four lever arm speeds (0,60,180 and 300°/sec). Maximal knee extensions at the different lever arm speeds were evaluated for peak torque, 30° torque and time to constant velocity. A fatigue test was evaluated by percent decline and by analysis of the power output at specific time intervals. Mean peak torque, 30° torque and time to constant velocity values were significantly different ($p < .05$) in the W-A and W-B conditions as compared to the control condition for all lever arm speeds except 300°/sec. Temperature alteration, passive or active, resulted in no significant change ($p < .05$) in the percent decline as determined by the fatigue test. Evaluation of the power output of the fatigue test indicated that passive cooling significantly ($p < .05$) lowered the power output compared to all other conditions. Interval analysis showed varied reductions of power caused by the different conditions. It was concluded that the significant changes found with active warm-up were not a Q_{10} effect, but rather the result of neuromuscular alteration in direct response to actual activity.

THE UNIVERSITY OF ARIZONA
GRADUATE COLLEGE

I hereby recommend that this dissertation prepared under my direction

by Richard William Cote' III

entitled The Relationship of Temperature to Strength and Power Production in Intact Human Skeletal Muscle

be accepted as fulfilling the dissertation requirement for the Degree

of Doctor of Philosophy.

Jack H. Wilmore — 7 June 1979
Dissertation Director — Date

As members of the Final Examination Committee, we certify that we have read this dissertation and agree that it may be presented for final defense.

Fred Roby — May 29, 1979
Date

Thomas N. Wagner — June 6, 1979
Date

Jack H. Wilmore — 7 June 1979
Date

Date

Date

Final approval and acceptance of this dissertation is contingent on the candidate's adequate performance and defense thereof at the final oral examination.

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Eight male subjects volunteered to participate in a study to determine the relationship between variations in Tm and the characteristics of strength and power development in intact muscle. The subjects were studied under control and four experimental conditions, two active warm-up conditions(W-A and W-B) and two passive warm-up conditions(heating and cooling).Each subject was tested on the Cybex II isokinetic testing device at four lever arm speeds (0,60,180 and 300°/sec).Maximal knee extensions at the different lever arm speeds were evaluated for peak torque, 30° torque and time to constant velocity.A fatigue test was evaluated by percent decline and by analysis of the power output at specific time intervals.Mean peak torque, 30° torque and time to constant velocity values were significantly different($p<.05$) in the W-A and W-B conditions as compared to the control condition for all lever arm speeds except 300°/sec. Temperature alteration,passive or active, resulted in no significant change ($p<.05$) in the percent decline as determined by the fatigue test.Evaluation of the power output of the fatigue test indicated that passive cooling significantly($p<.05$) lowered the power output compared to all other conditions.Interval analysis showed varied reductions of power caused by the different conditions.It was concluded that the significant changes found with active warm-up were not a Q_{10} effect, but rather the result of neuromuscular alteration in direct response to actual activity.

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Captain, U. S. Air Force

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SIGNED: Richard W. Coté III

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ABSTRACT

Eight male subjects volunteered to participate in a study to determine the relationship between variations in Tm and the characteristics of strength and power development in intact muscle. The subjects were studied under control and four experimental conditions. In the W-A condition, the subject exercised on an isokinetic testing device at 50% of his peak torque at a lever arm speed of 180°/sec, 30 extensions/min for 5 min. The W-B condition was identical to W-A except the subject exercised an additional 5 min at 60% peak torque immediately following W-A. The remaining two conditions changed Tm passively by 30 min of hot packs or ice packs.

For each of the 5 conditions, the subject was tested on the Cybex II isokinetic testing device at four lever arm speeds (0, 60, 180 and 300°/sec), two trials at each speed, follwed by a 30 sec fatigue test. Maximal knee extensions at the different lever arm speeds were evaluated for peak torque, 30° torque and time to constant velocity. The fatigue test was evaluated by percent decline and by analysis of the power output at specific time intervals.

The peak torque measurements exhibited a high degree of reliability with correlations of 0.90 or greater for all speeds. The coefficients of variation were found to be small with the highest value being 2.33% for 300°/sec. Tm's were changed an average of +2.9, +4.1, +4.3 and -14.5°C for W-A, W-B, passive heating and passive cooling respectively.

Mean peak torque, 30° torque and time to constant velocity values were significantly different ($p<.05$) in the W-A and W-B conditions as compared to the control condition for all lever arm speeds except 300°/sec. Mean 30° torque values for passive heating and cooling were significantly higher than the control condition ($p<.05$) at 60°/sec lever arm speed. Additionally, the mean 30° torque value for passive cooling was significantly lower than the passive heating value ($p<.05$) at 300°/sec lever arm speed. Temperature alteration, passive or active, resulted in no significant change ($p<.05$) in the percent decline as determined from the fatigue test. Evaluation of the power output of the fatigue test indicated that passive cooling significantly ($p<.05$) lowered the power output compared to all other conditions. Interval analysis showed that the W-B and passive heating caused significantly lower power outputs to occur in the second interval when compared to control. Except for the W-B condition, the last three intervals showed significant power reductions ($p<.05$) when compared to control. Additionally, the passive heating condition was significantly lower than the W-B condition ($p<.05$) at the third through the fifth intervals.

It was postulated that the significant changes seen from the active temperature alteration could be the result of (1) a Q_{10} effect on metabolism, (2) an increased ACh release at the neuromuscular end plate, (3) alterations in the action potential, (4) a Q_{10} effect on the contractile characteristic of the ST muscle fibers, and (5) a Q_{10} effect on the muscle spindles all combining to improve muscle synchronization. However, a comparable response to the Q_{10} effect should also have been

demonstrated for passive heating. Therefore, the significant changes found with active warm up were not a Q_{10} effect, but rather the result of neuromuscular alteration in direct response to actual activity. The significant differences of power output for the fatigue test intervals were thought to be caused by (1) muscle fiber inactivation by cold, (2) muscle fiber inhibition by fatigue, and (3) reduction of energy supply.

CHAPTER 1

INTRODUCTION

Temperature plays a critical role in most, if not all, biochemical processes. The average kinetic energy and the average velocity of molecules increases with increases in temperature, resulting in a greater probability for more effective, reaction-causing collisions. Reaction rates for chemical equations have been shown to double by an increase of $10^{o}C$ ($Q_{10} = 2.0$) (Netter, 1969; Shapiro and Stoner, 1966). There are limits, however, to the extent to which temperature can be raised before the onset of undesirable biological reactions, i.e., protein denaturization at high temperatures. By working within this limit, it would seem biochemically feasible that a rise in whole body temperature could be beneficial to the chemical reactions occurring within the body, or more specifically to metabolism.

Oxygen consumption has been shown to increase with a rise in body temperature (Abramson et al., 1957; Shapiro and Stoner, 1966). The tissue exchange of oxygen is also greater owing to a shift of the O_2 dissociation curve to the right, consequent to the rise in temperature (Barcroft and King, 1909). Edwards et al. (1972) have shown that even glycolysis is accelerated by a rise in temperature. They conclude that the accelerated rate of glycolysis is proportional to the high turnover rate of the high energy phosphate compounds.

The direct energy source for muscular contraction is adenosine triphosphate (ATP), a high energy phosphate compound. The hydrolysis of ATP is the essential energy releasing step for muscular contraction. It is this reaction that controls the speed of muscle shortening and tension development (Keul, Doll, and Keppler, 1972). The rate of force or power developed by the muscle is, in fact, proportional to the number of cross bridges that form between the protein filaments per unit of time (Dudel, 1975). ATP is necessary for the formation of the cross bridges, and is thus critical to the muscle's ability to produce power. Buller, Ranatunga, and Smith (1968) lowered the muscle temperature of cat limb muscle in vivo by 10°C and found the time to peak tension increased by 50-60%. This lengthened time interval represents a decrease of the muscle's rate of force or power development.

Temperature has also been shown to have marked physiological effects on living organisms. The nerve impulse travels faster and ionic permeabilities are increased with increases in temperature (Delbeke, Kopec, and McComas, 1978; Frankenhaeuser and Moore, 1963; Guttman, 1962; Ward and Thesleff, 1974). At the neuromuscular junction, a temperature increase facilitates the release of the quanta of acetylcholine (ACh) and increases the frequency of the miniature end plate potentials (MEPP) (Hubbard, Jones, and Landau, 1971; Ward, Crowley, and Johns, 1972).

Studies of muscle contractile properties have shown that with increasing temperature the isometric twitch tension decreases and isometric tetanic tension increases (Cullingham, Lind, and Morton, 1960; Hill, 1951; Truong, Wall, and Walker, 1964; Walker, 1949). Cullingham et al. (1960) found that the isometric tension of cat tibialis anterior,

in situ, was greatest at a muscle temperature of 38-40°C. Hill (1951) has suggested that the reason for the opposite effects of temperature on twitch and tetanus is that temperature has a greater effect on the onset of relaxation than for the rate of tension development. Walker (1960) arrived at a similar conclusion.

From the previous work cited, it can be concluded that a strong scientific base has been established to indicate that alterations of temperature can have positive, beneficial physiological and biochemical effects on an organism. However, it remains to be seen whether this beneficial effect of temperature change can be extrapolated from resting isolated muscle preparations to an exercising organism such as the human being, where performance or work output is the parameter used to determine if temperature alteration is beneficial.

In exercise or athletics, altering the temperature of the body, or more specifically, the muscle, has long been advocated as a means of improving performance. Temperature has been altered in two primary ways: (1) actively, where the body or muscle temperature is increased by physical work, and (2) passively where an external heat source (or cold source if temperature is to be lowered) is applied to the body or muscle to raise its temperature. The results of investigations utilizing active and passive warm-up and their relationship to performance have been contradictory.

Review of Literature

In the classic work by Asmussen and Bøje (1945), work performance was evaluated following both active and passive forms of temperature alteration or warm-up . A standard work task on a bicycle

ergometer was used as the criterion test. Rectal temperature (Tr) and muscle temperature (Tm) were measured as indices of temperature change. Active heating was accomplished by riding the ergometer for 30 minutes, and passive heating was done by radio diathermy or hot showers. An improvement in performance was demonstrated for both active and passive conditions. They also concluded that due to the relatively slow rise of Tr compared to the fast rise of Tm during exercise that the Tm was directly responsible for the improvement in work capacity.

A similar study by Muido (1947) produced similar results with active and passive warm-up proving beneficial to swimming performance at distances of 50, 200 and 400 meters. His active warm-up of jogging or bike riding for 10 minutes, however, was not specific to swimming, and, therefore, his Tm's did not show the magnitude of change reported by Asmussen and Bøje (1945). He concluded that it was blood or body temperature that was the critical factor responsible for improved performance.

Högberg and Ljunggren (1947) tested runners at 100, 400 and 800 meters after both a running warm-up and a 20-minute sauna bath. Active warm-up resulted in the greatest improvements, i.e., 3-4% at 100 meters, 3-6% at 400 meters and 2.5-5% at 800 meters. It was also shown that a 15-minute warm-up was better than a 5-minute warm-up but a 30-minute warm-up was no better than 15 minutes (active warm-up). Also, the benefit of warm-up on performance was lost after 45 minutes of rest. In a separate study, improved times for a 120 yard sprint were also found following active warm-up when using either untrained students or trained track runners (Blank, 1955).

Carlile (1956) found a one percent improvement of swimming performance with hot showers as a warm-up. He proposed a possible psychological influence on performance from warm-up and subsequently tested his proposal. He had the swimmers take long showers which they thought were detrimental to performance prior to their swims. Improvement was still found in their swimming performances. No relationship was found between Tr and their swimming performances.

In another study of warm-up and swimming performance, DeVries (1959) investigated four different warm-up procedures which included two active warm-ups, one specific (swimming) and one non-specific (calisthenics); and two passive warm-ups, hot shower and massage. Competitive swimmers were tested at a 100 meter sprint swim. Both forms of active warm-up resulted in significant improvement of the swim times where the passive warm-ups resulted in no improvement.

The specific or formal warm-up versus the non-specific or informal warm-up was further investigated by Thompson (1958). Swimming speed for 30 yards and swimming endurance (number of laps swum in 5 minutes) were improved only with formal warm-up. In an evaluation of strength using a dynamometer, only informal warm-up was employed and no increase in strength was found. No explanation was given as to why formal warm-up was not included in the strength protocol.

Power performance was significantly improved by warm-up in two studies by Pacheco (1957, 1959). Warm-up included running in place, isometric stretching and knee bends. All forms of warm-up produced significant improvements in the jumping ability of the subjects. In the 1957 study, psychological influences were evaluated by not informing the

subject that a "warm-up" study was in effect. Fifty subjects did deep knee bends as the warm-up activity and a significant improvement of jumping ability still resulted.

Michael, Skubic, and Rochelle (1957) and Rochelle, Skubic, and Michael (1960) found significant increases in softball throw for distance with warm-up. Rochelle et al.(1960) determined that the formal type of warm-up produced the best results for improvement. Monetary incentives, used as a control for psychological influences, did not produce any significant differences in performance.

A recent article investigating the influence of warm-up on running performance, demonstrated that warm-up was beneficial to performance in a 60 yard dash, 440 yard dash and a 1 mile run (Grodjinovsky and Magel, 1970). However, when the warm-up was classified as vigorous or easy, only the vigorous warm-up benefited the performance for the 1 mile run, while both vigorous and easy warm-ups benefited the 60 and 440 yard dashes.

The psychological effect of warm-up has been mentioned previously as an important factor to consider. In the only study dealing with this as the primary factor, Massey, Johnson, and Kramer (1961) found that when all knowledge of the warm-up was eliminated with hypnosis, no significant change was found in ergometer ride time. The warm-up employed, however, was of the non-specific type and Tr was not measured.

Hipple (1955) studied junior high school boys using the 50 yard dash as both a warm-up and the criterion task. Five consecutive dashes were run with the previously run dashes acting as warm-up. No benefit to performance was gained by the warm-up procedure. Sills and O'Riley

(1956), using a 10 minute walk and jog warm-up, also found no significant difference in running endurance performance.

Karpovich and Hale (1956) examined the effects of warm-up on performance in a three stage project. In the first stage, trained track athletes were tested at 440 yards with three types of warm-up: (1) deep massage, (2) placebo massage, and (3) active warm-up (running). Sixty runs were performed in all and no differences were found among the three warm-ups. In the second experiment, placebo massage was evaluated against a control (no warm-up) or cold condition and no difference was found between these conditions. In the last experiment, students were trained on the bicycle ergometer to accustom them to riding. An ergometer warm-up was compared to the cold or control condition. The criterion task was to complete 35 pedal revolutions as quickly as possible. No significant difference was found in performance, although the mean time was reduced by 0.5 seconds. They concluded that warm-up did not benefit performance.

Skubic and Hodgkins (1957) found no differences in speed (0.1 mile bike ride) or strength (softball throw) of women physical education majors between control and warm-up conditions. Warm-up conditions were both related, bike riding or softball throwing, and unrelated, jumping jacks.

Sedgwick (1964) used diathermy to passively heat the upper arm area, and evaluated strength and endurance changes by elbow flexion and dynamic grip respectively. Results showed a slight decrease in strength, which was not statistically significant and no change in endurance.

Active warm-up through finger and wrist exercises produced no effect on muscular endurance as measured by dynamic grip (Sedgwick and Whalen, 1964).

Purpose

It is apparent from the preceding review that the literature is equivocal on the relationship of temperature and performance improvement. Quite often when a number of investigators probe a particular problem the approaches are different and the subsequent results are difficult to equate and interpret. Much of the previous work has suffered from the inability to provide for adequate standardization and objectivity of measurement.

The purpose of this investigation was to study the relationship between variations in muscle temperature and the characteristics of strength and power development in human skeletal muscle. An isokinetic measuring device (Cybex II, Lumex Inc., New York City) was employed since it has proven to be an objective means of standardizing strength and power measurements in human intact skeletal muscle (Moffroid et al., 1969; Thorstensson, Grimby, and Karlsson, 1976). It is hypothesized that as muscle temperature is increased, strength or power, or both, will also be increased and so will endurance.

To test this hypothesis, temperature was altered both passively and actively and compared to a control condition. Active warm-up was accomplished in such a way as to provide for two distinct end points representing two different Tm's. The first active warm-up (W-A) required the subject to exercise for five minutes at 50% of the peak torque attained from a maximal knee extension at a lever arm speed

of 180° per second. W-B was an extension of W-A requiring the subject to exercise an additional five minutes at 60% of peak torque. Passive temperature changes were accomplished by the application of hot (to raise Tm) and cold (to lower Tm) packs for a 30-minute time period.

CHAPTER 2

METHODOLOGY

Subjects

Eight male subjects volunteered to participate in this study and their characteristics can be found in Table 1. Prior to giving their consent to participate, each subject was fully informed verbally and in writing as to the nature and possible risks associated with the study. The experimental protocol and subject consent form (see Appendix A) had been previously reviewed and approved by the University of Arizona Human Subjects Committee (see Appendix B). All of the subjects in this study had previously participated in other projects utilizing similar procedures. Therefore, it was assumed that each subject was fully acquainted with the protocol prior to beginning this project.

Muscle Temperatures

All muscle temperatures (Tm) were measured in the vastus lateralis muscle using a hypodermic probe inserted to a depth of 2.0 to 2.5 centimeters. A Yellow Springs Instrument (YSI) series 500 hypodermic probe was used in conjunction with a YSI Telethermometer model 46TUC. A calibration curve was determined for this probe and can be found in Appendix C. To facilitate insertion of the probe into the muscle, a small incision was made over the vastus lateralis muscle using a number 11 scalpel blade, following the injection of a 1% lidocaine solution as a local anesthetic.

Table 1. Physical characteristics of the subjects

Subject	Age (yr)	Height (cm)	Weight (kg)
1	26	175.3	81.6
2	23	167.6	60.3
3	23	177.2	70.3
4	32	169.6	67.2
5	24	175.3	63.5
6	30	172.1	55.8
7	26	177.2	64.9
8	30	177.8	72.6
$\bar{X}$	26.8	174.0	67.0
S.D.	3.5	3.8	8.0
$S_{\bar{X}}$	1.2	1.4	2.8

Pilot Project

Prior to beginning this experiment a pilot project was undertaken to determine if Tm for a relative work task would be similar in all subjects, and to determine if Tm was reproducible for the same work task on separate days. Saltin, Gagge, and Stolwijk (1968) had previously established the predictability of Tm for $\dot{V}O_2$ expressed as a percentage of $\dot{V}O_{2max}$. If a similar relationship could be established for the work protocol used in the present study, the necessity of taking individual Tm's on all subjects at each of the two active warm-up conditions would be unnecessary.

Four of the eight subjects were chosen to determine the stability of Tm between subjects. Each of these four subjects exercised on the Cybex II isokinetic device using both active warm-up protocols. During the first warm-up protocol (W-A) each subject exercised at 50% of his peak torque at a lever arm velocity of 180° per second, 30 extensions per minute for 5 minutes. The second warm-up protocol (W-B) was identical to W-A except the subject exercised an additional 5 minutes at 60% of peak torque immediately following W-A.

Tm's were taken prior to warm-up, and after the W-A and W-B protocols respectively. Each Tm was taken in duplicate, referred to as trial 1 and 2, and the entire testing sequence was repeated on two different days, referred to as days 1 and 2. Appendix D contains the individual measures for each day and trial.

The results of the pilot project are found in Table 2. No significant differences ($p < .05$) were found between trial to trial and day to day mean values. Also, no significant differences ($p < .05$) were

Table 2. Variations in mean muscle temperatures (^{o}C) for within day and between day comparisons under all three measuring conditions

	Rest		W-A		W-B	
	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2
$\bar{X}$	32.87	32.83	35.73	35.78	36.97	36.95
S.D.	0.40	0.47	0.24	0.26	0.11	0.09
$S_{\bar{X}}$	0.14	0.17	0.09	0.09	0.04	0.03
t	--	0.12	--	0.44	--	0.34
	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2
$\bar{X}$	32.96	32.62	35.74	35.77	36.93	36.99
S.D.	0.19	0.40	0.14	0.36	0.09	0.10
$S_{\bar{X}}$	0.09	0.20	0.07	0.18	0.05	0.05
t	--	1.53	--	0.14	--	0.94

found between subjects. It was concluded that Tm was reliable and that the two warm-up protocols would produce consistent and similar Tm values in each subject.

Testing Battery

A Cybex II isokinetic testing device (Lumex Inc., New York City) was used to evaluate the strength and power output for each subject under each of the four experimental conditions, i.e., W-A, W-B, passive heating and passive cooling. This device consists of a lever arm attached to a mechanical hydraulic head (see Figure 1). Any body segment can be attached to the lever arm and movement can be studied through any range of motion. In this study, the lower right leg was attached to the lever arm to study maximal leg extension. A range of motion of 90° was used with 0° representing full leg extension. The lever arm speed can be preset and maintained at a constant velocity. The resistance is then proportional to the ability of the muscles to generate tension at each point during the range of motion.

The subjects were secured by a seat belt to a chair with an adjustable back support, providing stabilization in an attempt to isolate the muscle group specific for leg extension. The mechanical rotation or pivot point was aligned with the subject's anatomical pivot point about the knee. Each subject was permitted two practice trials to familiarize himself with each speed before the two test trials were recorded on a Gilson five channel recorder. The subjects were encouraged to exert maximal muscular effort throughout the entire range of motion on all trials.

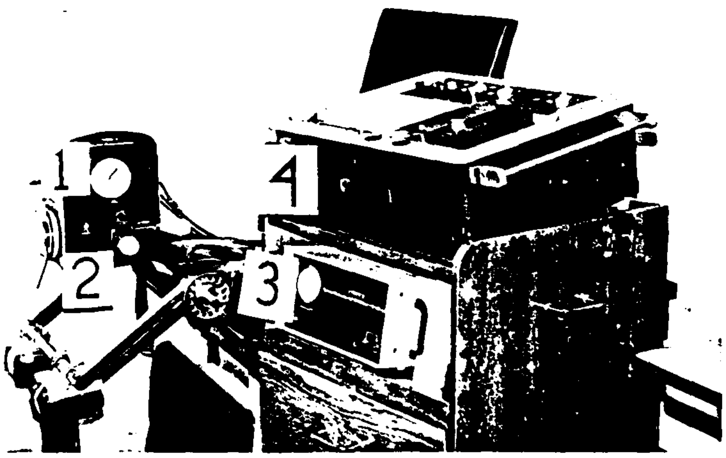


Figure 1. Cybex II isokinetic measuring device

1. Head
2. Lever Arm
3. Speed Control
4. Gilson 5 channel recorder

Each subject was tested at four preset lever arm velocities: (1) 0° per second, i.e., isometric; (2) 60° per second; (3) 180° per second; and (4) 300° per second. Simultaneous recordings of torque, measured at a damping selection of two, and angular displacement were obtained for each of the four velocities. Damping of the instrument is accomplished by using one of four different capacitance circuits to suppress the oscillitory effects of the input energy. A damping of 0 provides no effect and a damping of 4 provides maximum suppression of the energy oscillations. Calibration of the Cybex II device was done by hanging known weights from the lever arm at the 0° position. The torque produced was calculated as the force times the length of the lever arm, and was expressed in newton-meters (Nm). The use of the Cybex II isokinetic device has been similarly described by Thorstensson et al. (1976).

The peak torque value, or the peak isometric value at 0° per second lever arm speed, was used as the index of strength. The peak value is defined as the highest torque value measured during leg extension at each of the lever arm speeds. Perrine and Edgerton (1978) have questioned the use of peak torque values due to problems with inertia, and energy oscillations throughout the total (muscle-instrument) system. Therefore, a torque reading was also made at 30° of extension to minimize or eliminate the above mentioned problems. A third parameter, time to constant velocity, was measured to determine if a subject's ability to accelerate could be improved through temperature manipulation. This measurement is defined as the time it takes to accelerate the limb-lever arm to the preset velocity. This time can be measured from the recording

of the torque and angular displacement by measuring the time from initiation of movement, measured from the angular displacement curve, to the beginning of measurable torque. The relationship of these parameters can be seen in Figure 2.

The fatiguability of the leg extensors was evaluated for all five conditions in all subjects using a modification of the procedure described by Thorstensson and Karlsson (1976). The lever arm speed of the Cybex II was kept at 180^{o} per second but maximal knee extensions were performed for 30 seconds, rather than the 60 second period used by Thorstensson and Karlsson (1976). An average of 25 contractions (25.1 ± 0.97) were performed during the 30 second test. The decline of peak torque was measured as a percent of initial values by comparing the mean peak torque of the last three contractions to the mean peak torque of the first three contractions.

Power was evaluated on selected intervals of the fatigue test. Power is defined as work per unit of time. Work was determined by using planimetry to calculate the area under the torque curve (Figure 2) and time was evaluated from the speed of the recorder and the recordings themselves. The fatigue test recordings were divided into five six-second intervals, each interval containing five leg extensions. The last extension of each interval was selected as representative of the interval.

Testing Sequence

As was previously mentioned there were five conditions evaluated in this project. These conditions were separated into two phases.

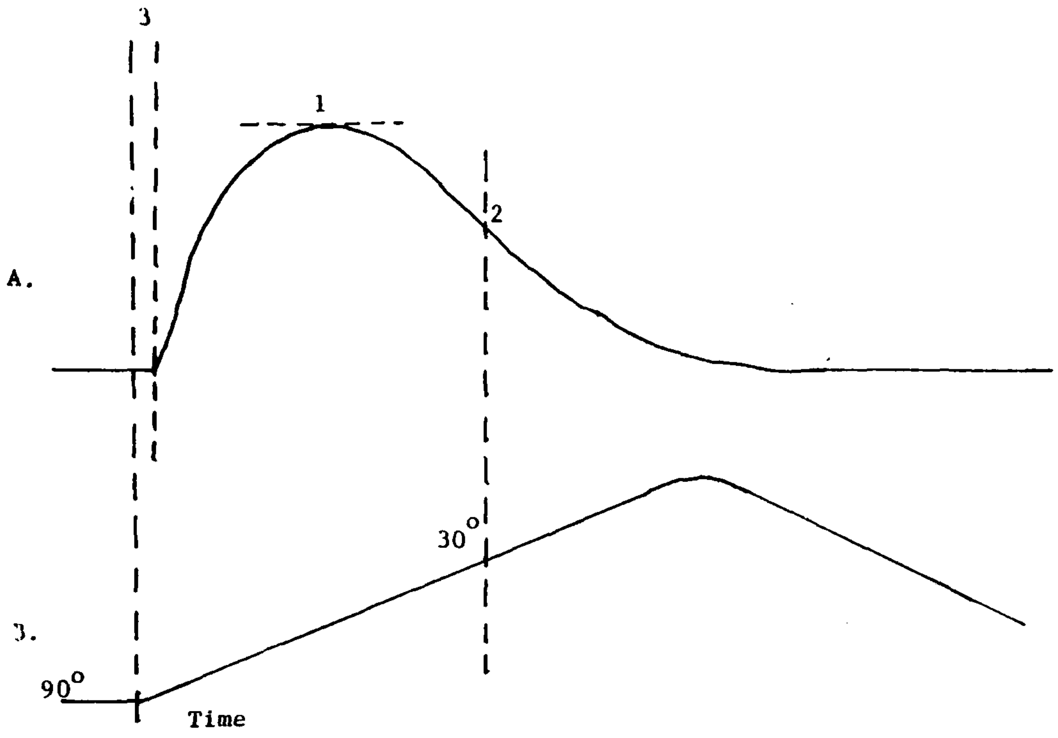


Figure 2. Sample output from Cybex II isokinetic device

A. Torque curve: 1-peak torque; 2-30° torque; 3-time to constant velocity
B. Angular displacement curve

Phase I consisted of the control condition and the two active warm-up conditions. Phase II was composed of a repeat of the control condition and the passive heating and cooling conditions.

In Phase I, the active conditions were those described in the pilot project as W-A and W-B. The passive heating for Phase II was achieved by placing hydrocollator pads on the thigh area of the right leg for a period of 30 minutes, and passive cooling utilized ice packs for a period of 30 minutes. The order of the testing sequence can be seen in Table 3.

Statistical Analysis

All data were analyzed using analysis of variance repeated measures design (Bruning and Kintz, 1968). A Duncan multiple range test was used to determine those means between which differences existed. A 0.05 level of significance was selected for all analyses. Additionally, in the pilot project analysis and the fatigue test power analysis, student t test and one and two way analyses of variance were employed (Bruning and Kintz, 1968).

Table 3. Testing sequence for phases I and II

		Peak Torque	30^{o} Torque	Time to Constant Velocity	Fatigue Test	Tm
Phase I	Day 1	Control	Control	Control	Control	*
	Day 2	W-A, W-B	W-A, W-B	W-A, W-B	W-B	*
	Day 3	--	--	--	W-A	*
Phase II	Day 1	Control, Passive heating	Control, Passive heating	Control, Passive heating	Passive heating	Passive heating
	Day 2	Passive cooling	Passive cooling	Passive cooling	Passive cooling	Passive cooling

*From the conclusion reached by the pilot project no Tm's were measured in this phase

CHAPTER 3

RESULTS

Reliability

Reliability of the Cybex II isokinetic torque measurements were determined with day to day, test-retest data (control versus control), and exhibited significant correlations of 0.98, 0.97, 0.94 and 0.90 for lever arm speeds of 0^{o} per second, 60^{o} per second, 180^{o} per second and 300^{o} per second respectively. A similar finding for the 180^{o} per second speed was reported by Johnson and Siegel (1978). The coefficients of variation for 0^{o} per second, 60^{o} per second, 180^{o} per second and 300^{o} per second were calculated to be 2.30%, 1.62%, 1.93% and 2.33% respectively.

Muscle Temperatures

The Tm values for the active warm-up conditions can be found in Table 2 (statistical summary) and in Appendix D (individual values). Mean temperature changes from control to W-A and from control to W-B were $+2.9^{o}C$ and $+4.1^{o}C$ respectively. The data for both passive conditions can be found in Table 4 (statistical summary) and Appendix E (individual values). Passive heating was found to raise the mean Tm by $4.3^{o}C$ while passive cooling lowered the mean Tm by $14.5^{o}C$.

Table 4. Statistical summary of temperature changes in the passive warm-up conditions

	Control	Passive Heating	Control	Passive Cooling
$\bar{X}$	33.3	37.6	33.9	19.4
S.D.	0.76	0.61	0.77	3.70
$S_{\bar{X}}$	0.27	0.22	0.27	1.30

Peak Torque

The mean peak torque values for each of the five conditions are depicted in Table 5. Peak torque was found to be significantly different from control ($p<.05$) in only the active forms of temperature alteration at all but the 300° per second speed. Percent changes from control are also shown for each condition and lever arm speed. Individual peak torque values for all speeds and under all conditions can be found in Appendix F.

30° Torque

Individual 30° torque values for the speeds of 60° per second, 180° per second and 300° per second under all conditions can be found in Appendix G. The mean values and percent differences from control are shown in Table 6. Significant differences from control values ($p<.05$) were found for the 60° per second speed in the active and passive conditions and the 180° per second speed in the active conditions. At 300° per second passive cooling was significantly lower than passive heating.

Time to Constant Velocity

The mean time to constant velocity was significantly lower ($p<.05$) in the W-A and W-B conditions at 60 and 180° per second lever arm speed (Table 7). No significant changes were noted in the passive conditions. Individual values for the three speeds under all of the conditions can be found in Appendix H.

Table 5. Mean peak torque (Nm) values for active warm-up, passive heating and passive cooling

Speed	Active					Passive					
	Control	Warm-up A	% Δ	Warm-up B	% Δ	Control	Heating	% Δ	Cooling	% Δ	
	242.0	260.4*	+7.6	258.5*	+6.8	241.3	249.8	+3.5	258.8	+7.3	$\overline{X}$
0^{o}/sec (Isometric)	50.8	58.1		56.5		56.8	54.0		50.4		S.D.
	18.0	20.6		20.0		20.1	19.1		17.8		$S_{\overline{X}}$
	177.4	188.3*	+6.1	187.0*	+5.4	174.8	175.8	+0.6	174.8	0.0	$\overline{X}$
60^{o}/sec	35.5	36.5		34.4		41.4	37.3		53.0		S.D.
	12.5	12.9		12.2		14.6	13.2		18.7		$S_{\overline{X}}$
	106.8	116.6*	+9.2	112.4*	+5.2	105.8	107.5	+1.7	101.3	-4.3	$\overline{X}$
180^{o}/sec	23.2	24.8		25.8		29.5	28.7		24.1		S.D.
	8.2	8.8		9.1		10.4	10.2		8.5		$S_{\overline{X}}$
	67.0	71.6	+6.9	68.1	+1.6	68.3	65.5	-4.0	60.0	-12.1	$\overline{X}$
300^{o}/sec	14.7	19.0		17.3		21.1	17.3		14.5		S.D.
	5.2	6.7		6.1		7.5	6.1		5.1		$S_{\overline{X}}$

*Significantly different from control ($p < .05$)

Table 6. Mean torque (Nm) at 30° of extension for active warm-up, passive heating and passive cooling

Speed	Active					Passive					
	Control	Warm-up A	% Δ	Warm-up B	% Δ	Control	Heating	% Δ	Cooling	% Δ	
	97.0	105.6*	+8.9	101.7*	+4.6	97.5	106.0*	+8.7	112.0*	+14.9	$\bar{X}$
60°/sec	21.5	24.8		22.1		38.7	41.5		39.7		S.D.
	7.6	8.8		7.8		13.7	14.7		14.0		$S_{\bar{X}}$
	95.7	103.0*	+7.5	100.7*	+4.9	87.8	94.5	+7.7	90.8	+3.4	$\bar{X}$
180°/sec	23.9	27.6		26.0		35.1	35.6		29.9		S.D.
	8.4	9.7		9.2		12.4	12.6		10.6		$S_{\bar{X}}$
	65.8	70.4	+7.0	67.6	+2.7	61.8	66.5	+7.7	57.5#	-6.9	$\bar{X}$
300°/sec	14.7	18.9		17.4		19.4	21.6		15.8		S.D.
	5.2	6.7		6.2		6.9	7.7		5.6		$S_{\bar{X}}$

*Significantly different from control ($p < .05$)
#Significantly different from passive hot condition ($p < .05$)

Table 7. Mean times (sec) to constant velocity for active warm-up, passive heating and passive cooling

	Active			Passive			
Speed	Control	W-A	W-B	Control	Heating	Cooling	
	.034	.029 *	.028 *	.035	.038	.039	$\overline{X}$
60^{o}/sec	.005	.004	.005	.005	.005	.004	S.D.
	.002	.001	.002	.002	.002	.001	$S_{\overline{x}}$
	.048	.043 *	.043 *	.050	.050	.050	$\overline{X}$
180^{o}/sec	.005	.005	.005	.017	.013	.013	S.D.
	.002	.002	.002	.006	.005	.005	$S_{\overline{x}}$
	.065	.064	.066	.071	.074	.078	$\overline{X}$
300^{o}/sec	.011	.007	.012	.020	.017	.020	S.D.
	.004	.003	.004	.007	.006	.007	$S_{\overline{x}}$

*Significantly different from control ($p < .05$)

Fatigue Test

Table 8 depicts the percent decline in peak torque over the 30 second duration of the fatigue test. No significant differences from control values ($p < .05$) were found for any of the four conditions. Individual values for percent decline under all conditions are located in Appendix I.

Further analysis was performed on the results of the fatigue test and these results are shown in Tables 9 and 10 with the corresponding individual values located in Appendices J and K. No significant difference from the control values ($p < .05$) was found for the mean of the first five knee extensions for any of the four conditions. In evaluation of the five intervals of the fatigue test (see the Methodology chapter for a definition of interval) during the five conditions, it was found that the subjects had a significantly lower power output for the cold condition as compared to the other conditions ($p < .05$). In all conditions, a significant reduction of power was seen with each successive interval ($p < .05$).

In all five intervals, the cold condition was significantly lower than all other conditions ($p < .05$). The passive heating condition was significantly lower ($p < .05$) than control for all but the first interval. It was also significantly lower than W-A ($p < .05$) at interval 2 and W-B at intervals 3, 4 and 5. The W-B condition was significantly lower than control ($p < .05$) for all but the first and third intervals and significantly lower ($p < .05$) than W-A in the fourth interval. Significantly lower ($p < .05$) than control values were found for the W-A condition in intervals 3, 4 and 5 only.

Table 8. Mean decline (%) of the first three peak torques to the last three peak torques at the conclusion of the 30 second fatigue test

	Control	Active		Passive	
		W-A	W-B	Heating	Cooling
$\bar{X}$	29.4	35.5	28.5	30.9	30.8
S.D.	8.9	12.5	10.5	9.2	7.7
$S_{\bar{X}}$	3.1	4.4	3.7	3.3	2.7

Table 9. Mean power output ($Nm \cdot sec^{-1}$) for the mean of the first five knee extensions during the 30 second fatigue test

	Control	Active		Passive	
		W-A	W-B	Heating	Cooling
$\bar{X}$	109.6	107.9	111.0	109.3	101.1
S.D.	32.8	26.5	32.6	34.9	33.1
$S_{\bar{X}}$	11.6	9.4	11.5	12.4	11.7

Table 10. Mean power output ($Nm \cdot sec^{-1}$) of every fifth knee extension during the 30 second fatigue test

Time Interval		1 6 sec	2 12 sec	3 18 sec	4 24 sec	5 30 sec
Control	$\bar{X}$	271.9	266.4	240.9	222.7	206.4
	S.D.	69.0	59.0	53.6	58.8	45.0
	$S_{\bar{x}}$	24.4	20.9	19.0	20.8	15.9
W-A	$\bar{X}$	277.4	261.6	227.0 [2]	200.3 [2]	182.1 [2]
	S.D.	72.9	63.1	49.8	48.0	52.1
	$S_{\bar{x}}$	25.8	22.3	17.6	17.0	18.4
W-B	$\bar{X}$	284.0	256.7 [2]	239.1 [3]	214.4 [2,3]	190.0 [2]
	S.D.	67.0	57.9	59.6	47.5	45.2
	$S_{\bar{x}}$	23.7	20.5	21.1	16.8	16.0
Passive Heating	$\bar{X}$	276.1	252.5 [2,3]	228.2 [2,4]	199.1 [2,4]	177.2 [2,4]
	S.D.	68.0	61.3	53.3	49.8	39.5
	$S_{\bar{x}}$	24.0	21.7	18.8	17.6	14.0
Passive Cooling	$\bar{X}$	254.9 [2]	217.3 [1]	200.3 [1]	182.1 [1]	164.5 [1]
	S.D.	78.8	56.3	58.4	55.5	36.4
	$S_{\bar{x}}$	27.9	19.9	20.7	19.6	12.9

1. Significant (p .05) from all other conditions
2. Significant (p .05) from control condition only
3. Significant (p .05) from W-A condition only
4. Significant (p .05) from W-B condition only

CHAPTER 4

DISCUSSION

Most previous research dealing with the relationship of temperature to force production in muscle have used isometric contraction as the criterion test and changed the Tm passively with air or water baths. Cullingham et al. (1960), Hill (1951), and Truong et al. (1964) found that increasing muscle temperature resulted in a concomitant increase in isometric tension. Cullingham et al. (1960) and Close (1972) have shown a decrease of isometric tension with decreasing muscle temperature. Maximal isometric tension was found to be greatest at a Tm of 38-40^{o}C and drops of 30-50% in tension were found at Tm's less than 20^{o}C (Cullingham et al., 1960; Close, 1972). Also, Binkhorst, Hoofd, and Vissers (1977) found that an increase in temperature was accompanied by increases in the force production at different velocities, except for the force at zero velocity, F_o (isometric tension). This resulted in a flattening, reduction of the hyperbolic curvature, of the force velocity curve with increasing velocities. Except for the findings of the Binkhorst et al. (1977) study, the results of the present study do not agree with the cited investigators under conditions of isometric contraction. With respect to dynamic contraction, the results of this study do not agree with the findings of Binkhorst et al. (1977) where the force velocity curve shifted to the right (Figure 3). Significant differences were found for the 30^{o} torque at 60^{o} per second

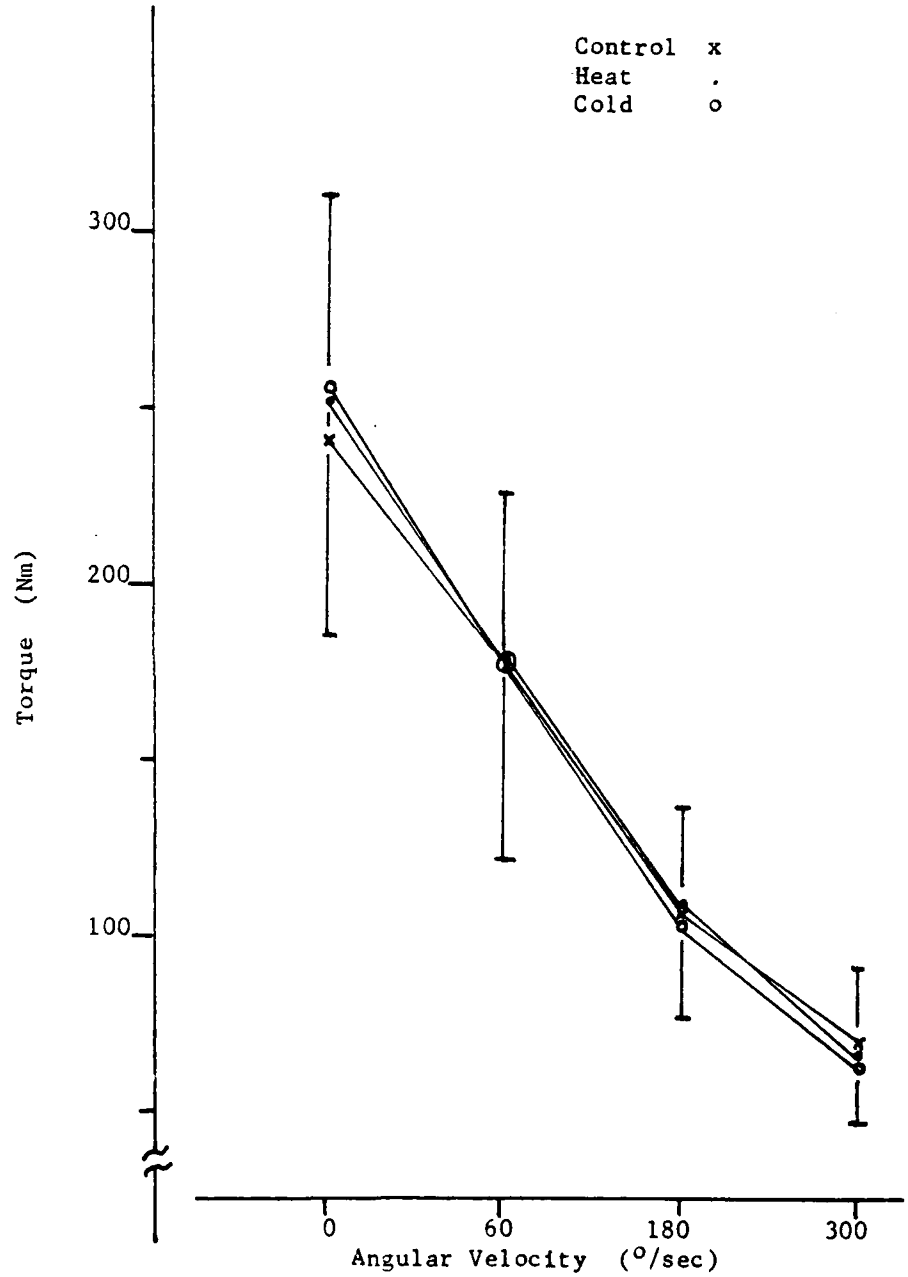


Figure 3. Mean peak torque for passive heating and cooling and control

(passive heating and cooling from control) and at 300° per second (passive cooling from passive heating) (Figure 4). The physiological significance of the mentioned differences is unexplainable at this time.

Two important factors to consider should be mentioned here. The first factor is a methodological limitation of the present study. Due to heavy demands for the available equipment, it was necessary to compress the data collection period for the passive heating treatment to accommodate the availability of the hydrocollator. It was, therefore, impossible to randomize the treatments of Phase II of this project. Second, it could be assumed that the greater the thigh skinfold of the subject the smaller the increment or decrement in Tm with passive heating or cooling. Figure 5 graphically depicts the relationship of thigh skinfold to Tm changes. It can be seen from this figure that the thickness of the thigh skinfold did not produce similar results for heating and cooling. A Spearman's rank order correlation between Tm's of passive heating and cooling was not significant (rho = 0.43, $p < .05$). These factors could have adversely affected the data and increased the within treatment variability. This possibility is borne out by an exceptionally large error term encountered in the treatment by subjects analysis of variance.

The major finding of this investigation was the significant increase in both the mean peak torque and the mean 30° torque values over the control values as a result of the two active warm-up conditions (Figures 6 and 7). The increase of torque values found with an increase in temperature could be explained either from a biochemical point of view or from a physiological point of view. The Q_{10} effect on chemical

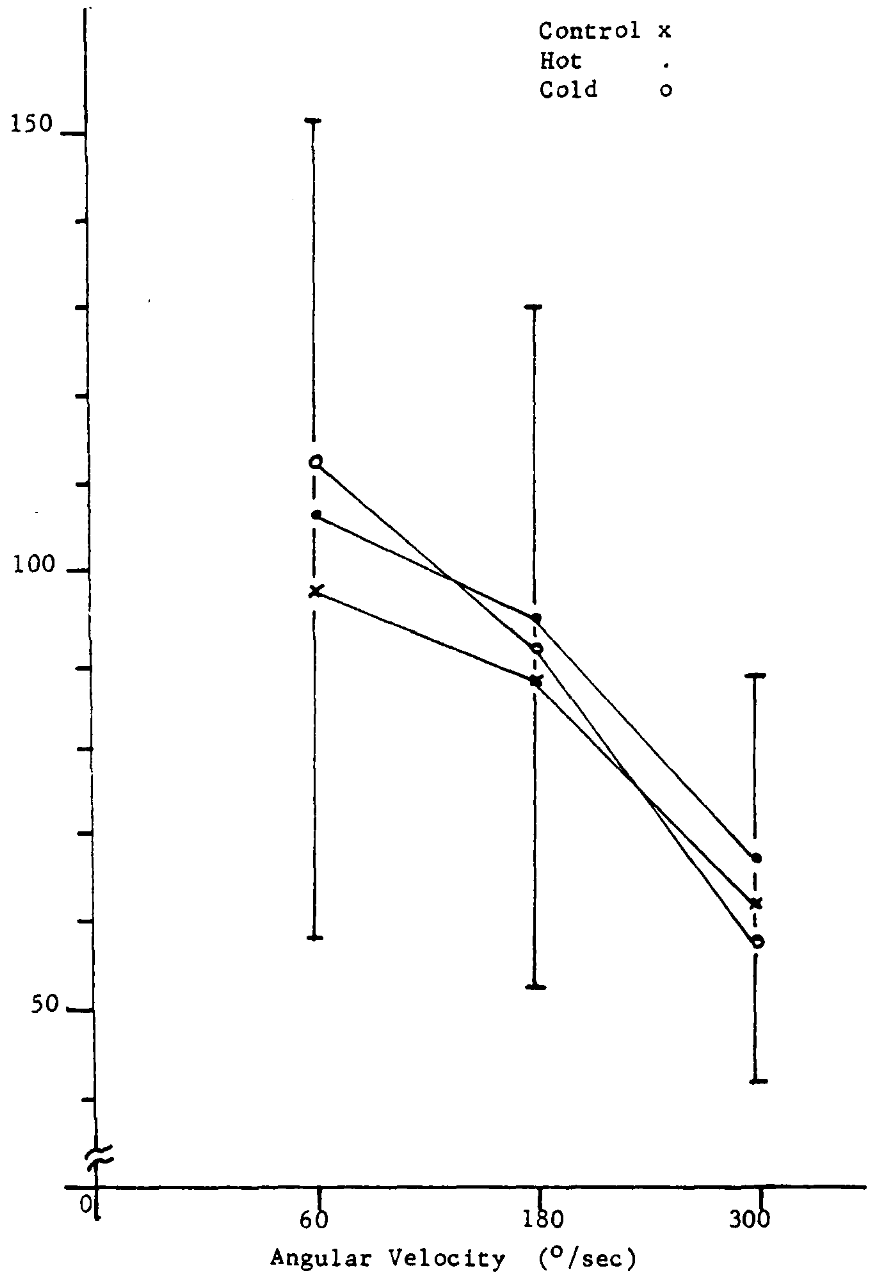


Figure 4. Mean torque at 30^o extension for control and passive heating and cooling

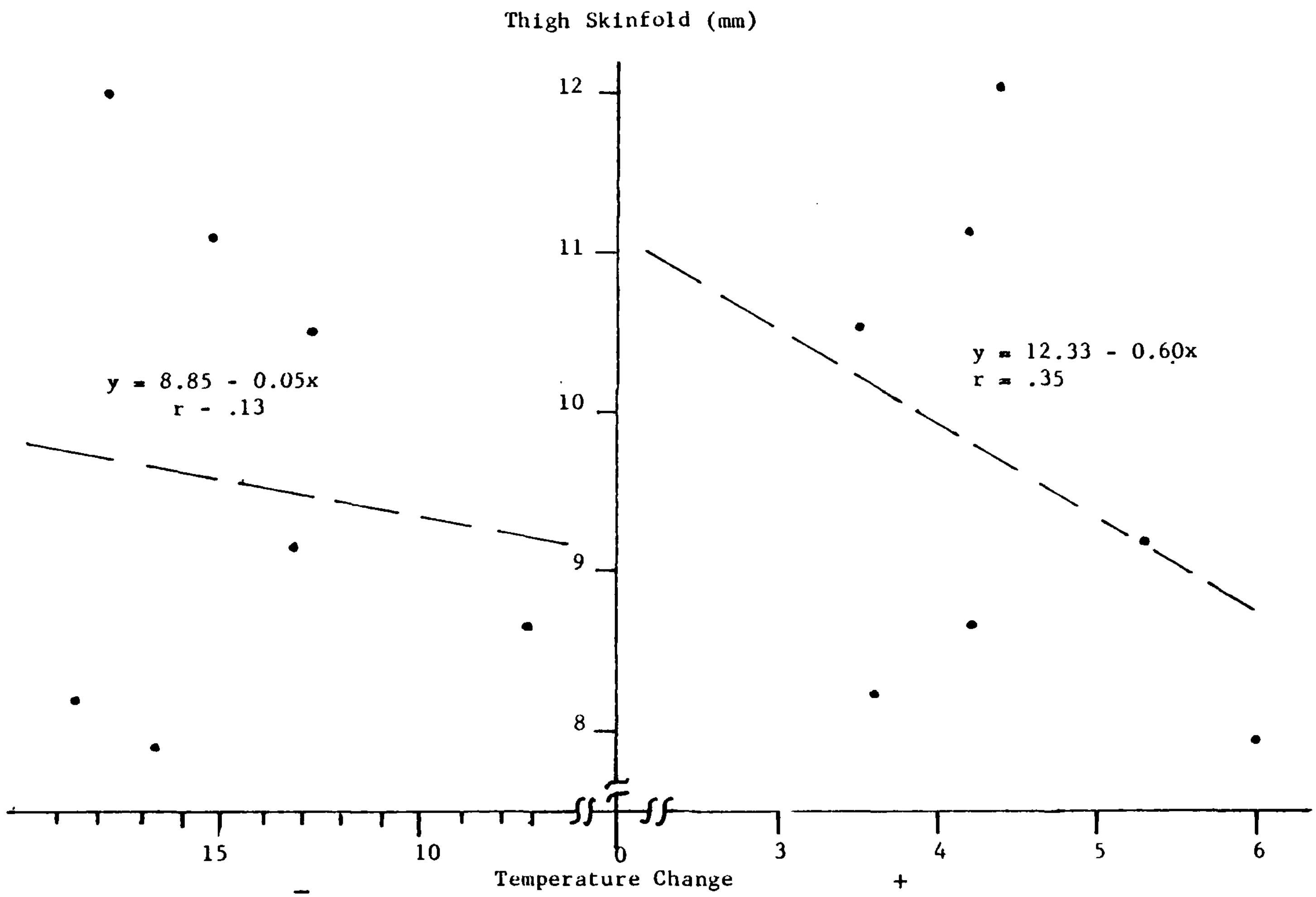


Figure 5. The relationship of thigh skinfold measures to changes of muscle temperature

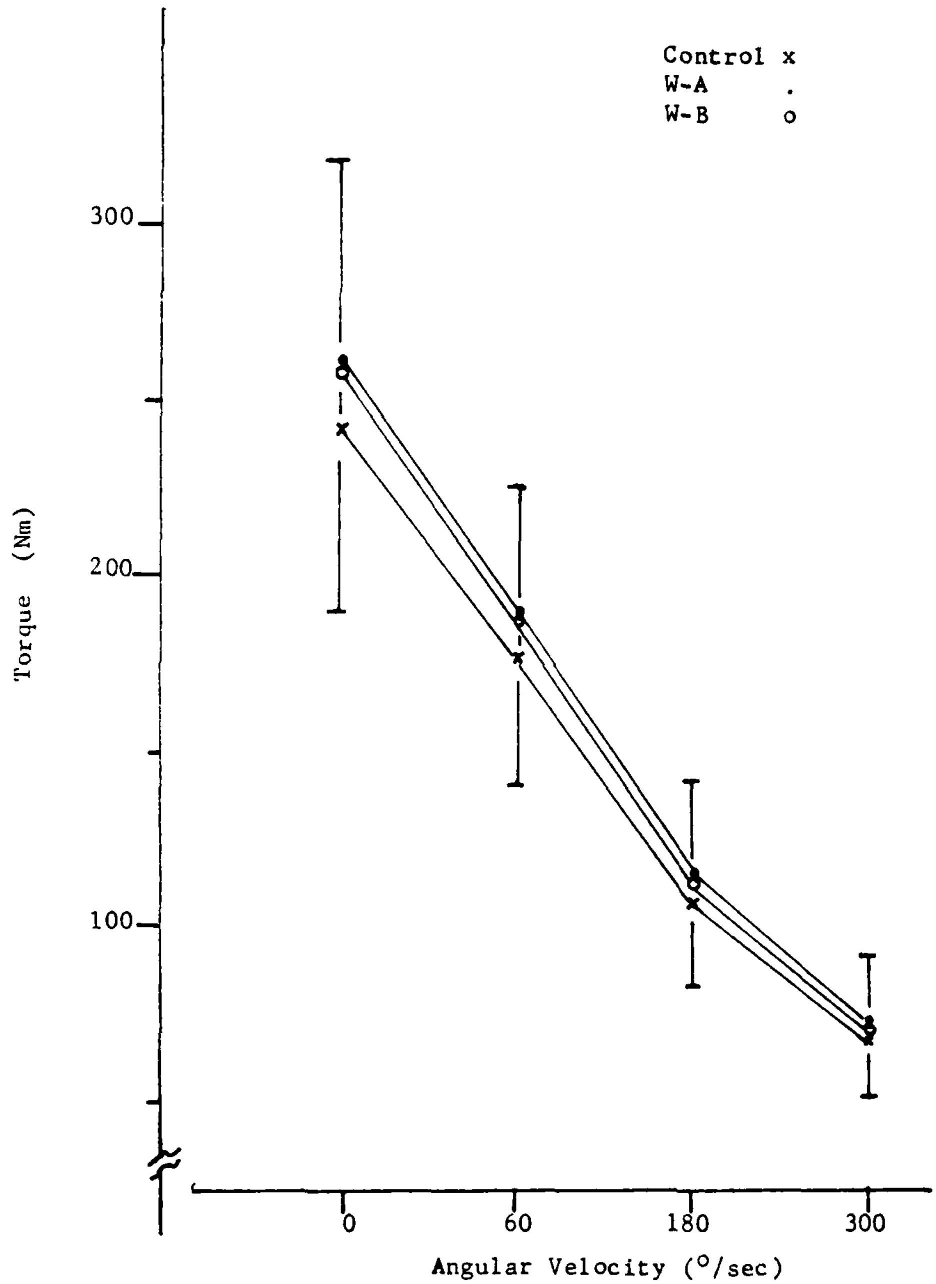


Figure 6. Mean peak torque for active warm-up conditions and control

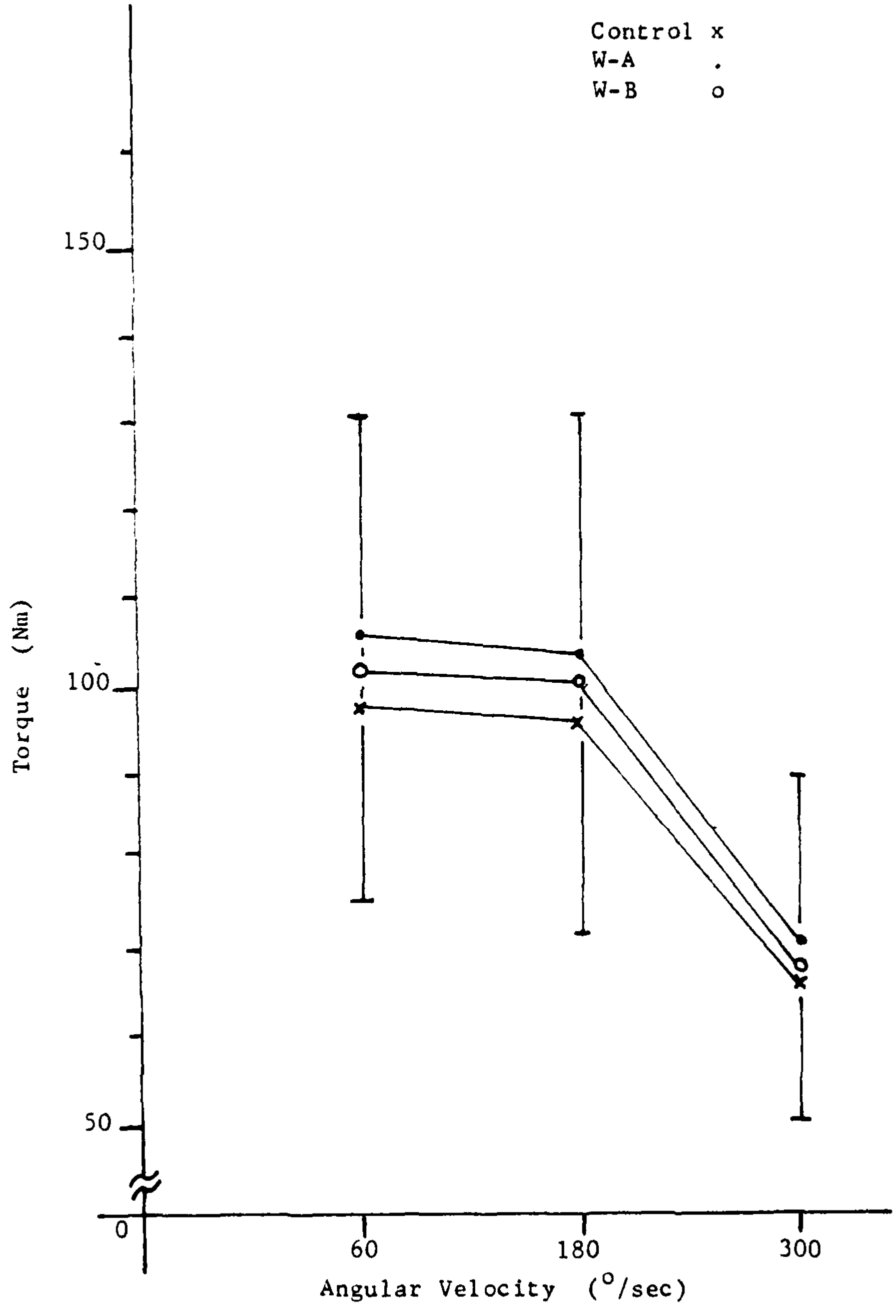


Figure 7. Mean torque at 30° extension for control and both active warm-up conditions

reactions has been documented previously (Netter, 1969; Shapiro and Stoner, 1966). Below the denaturation temperature of enzymes, the reaction rate of chemical equations will nearly double for every $10^{o}C$ rise in temperature (Bhagavan, 1974) ($Q_{10} = 2.0$). The key to energy production is the hydrolysis of ATP, a chemical reaction. Thus, an increase in the breakdown of ATP, enhances the rate of force development by the muscle. The force development of the muscle is proportional to the number of cross - linkages formed per unit of time. The faster the breakdown of ATP the greater is the number of linkages formed per unit of time, thus increasing potential force development. Additionally, oxygen consumption rises with increasing body temperature indicating an increased metabolism. This increase in metabolism is a result of the increase in the velocity of the chemical reactions associated with energy production.

The excitation of muscle is another critical factor to be considered when investigating possible sites where force production can be facilitated. If the excitation of muscle can be refined or improved then that muscle has a potential for producing optimum force output. As temperature increases, the quanta release of ACh increases, and the frequency of the MEPP's also increase concomitantly (Hubbard et al., 1971; Ward et al., 1972). It can be postulated that the greater release of quanta per unit of time can increase the sensitivity of the neuromuscular junction to stimulation. The maximum rate of rise of the action potential (AP) of innervated and denervated rat extensor digitorous longus (EDL) muscle fibers has been shown to increase with increasing temperature (Ward and Thesleff, 1974). They also found a decline in the

amplitude of the AP with increasing temperature which they felt was a result of the greater acceleration of the falling phase than the rising phase. Delbeke et al. (1978) have found a shorter absolute refractory period (ARP) and relative refractory period (RRP) with increasing temperature in nerve and muscle. These factors point to a greater ability to produce action potentials at an increased rate over normal with elevated temperature. All of these effects could act synergistically to provide greater sensitivity, thus improving the muscle's ability to synchronize its contractile mechanism. This increased synchronization of muscle fibers results in a greater force output.

Torque production at the high speeds is dependent on the percent of fast twitch (FT) muscle fibers (Thorstensson et al., 1976). They reported a positive linear relationship for the maximal knee extension velocity and percent of FT muscle fibers. They also showed a positive linear relationship between the percent of maximum voluntary isometric contraction (MVC) attained at 180° per second and percent FT muscle fibers. These relationships illustrate the greater dependence of fast contractions on FT muscle fibers. It is tempting to postulate that the temperature change in this study might have positively influenced only the slow twitch (ST) muscle fibers since no significant change occurred at the 300° per second speed.

Recently, Mense (1978) has shown that the afferent outflow activity from resting muscle spindles strongly depends upon Tm. Muscle spindles provide information to the central nervous system (CNS) relative to the length of the muscle via type Ia and Ib afferent nerve fibers. If the muscle spindle is stretched the AP's transmitted back to the CNS

increase in frequency. When a muscle contracts or shortens, the tension on the muscle spindle is relaxed and the discharge rate of the Ia fibers is reduced. With increasing temperature, the Ia activity is increased with a concomitant increase of stretch information being provided to the CNS. It is possible that the increase of afferent information could enhance neuromuscular sensitivity and work synergistically with the actions of ACh, AP and ARP to provide greater neuromuscular synchronization. It should be pointed out that this work has been conducted solely on resting muscle, thus reactions under conditions of exercise are presently unknown.

There is a distinct possibility that the significant changes in peak torque could have been associated with mechanical energy oscillations. The peak torque measured depends upon the force (torque) and the acceleration according to Newton's Laws of Motion. When the leg catches the lever arm, the acceleration will be proportional to the force (mass is constant). If the acceleration should increase then the force produced will also increase causing the peak torque to be increased also. As the time to constant velocity is shortened (increasing acceleration) the peak torque should also increase. Perrine and Edgerton (1978) feel that this potential limitation makes the peak torque less than desirable as a true measure of the muscle's ability to produce tension. They suggested the use of 30° torque values to eliminate the problem. The results of the present study show that when peak torque increased and time to constant velocity decreased, the 30° torque increased also. This suggests that either the 30° torque is no better a measure than the peak torque, or that temperature truely had a significant effect upon force

(torque) output. It is unlikely that the former is true since the reasoning for selection of the 30° torque value was to enable the subject's muscle to complete its initial energy buildup to full tension and to allow the inherent energy oscillations of the muscle-instrument system to subside (Perrine and Edgerton, 1978). Thus, it would seem that the active temperature change significantly affected the force output.

The previously cited explanations which have been offered to explain the results of the active temperature alterations are valid for any temperature change, active or passive. It would seem that if a true Q_{10} effect existed in this study it would have equally affected force production under the passive heating treatment. However, it did not cause similar results (within the limitations of this study). It therefore seems unlikely that the active warm-up increments in force production resulted from a Q_{10} effect, but rather from some neuromuscular effect resulting directly from the actual activity itself.

The results from Table 7 show that neither active nor passive temperature alterations had an effect on the muscle's fatiguability. It is difficult to equate the fatigue test used in this study and those endurance tests which have been commonly employed in previous warm-up studies. In the former, time was held constant where in the latter time was the measured variable. It could be said, though, that the lack of observed changes in the muscle's ability to withstand fatigue would indicate that endurance would not change due to its direct relationship to fatigue. No changes in dynamic grip endurance were found by Sedgwick and Whalen (1964) for both active and passive (Sedgwick, 1964) types of warm-up. In contrast, Thompson (1958) found endurance to improve with

active warm-up but use of a criterion test of a 5 minute swim opens up the criticism of possible psychological influences. It is the author's view that the 5 minute swim test does not provide adequate control of the subject by the investigator. The subject is permitted to set his own pace which can be influenced by his personal feelings and state of motivation at that time. The nature of the fatigue test in this study and the subsequent results seem to indicate that the muscle's ability to withstand fatigue is not affected by temperature change.

The significant reduction of power at each of the five intervals of the fatigue test for the passive cooling condition compared to all other conditions indicates the muscles failing ability to maintain each contraction throughout the range of motion. This could be caused by some muscle fibers becoming inactive as a result of the passive cooling, as shown by Clarke, Hellon, and Lind (1958). They concluded that at Tm below 27°C a proportion of the more superficial muscle fibers do not contract as a result of interference in nervous or neuromuscular transmission. Cullingham et al. (1960) have suggested that there is a persistance of depolarization of the motor end plates at low temperature. The lowest muscle temperatures are found superficially, therefore the inactivation of these fibers could be due to the constant depolarization which prevents stimulation or activation.

Active or passive warming also seems to negatively effect muscle power output but only in the latter stages of the fatigue test (see Table 9). The greatest drop in power output occurs at the earliest point in the fatigue test (interval 2) for both the W-B and the passive heating conditions. It is interesting to note that these two conditions are very

similar in temperature change, the former being 4.1°C and the latter being 4.3°C. The remaining three intervals, except for the third interval of the W-B condition, for the active and passive heating conditions, all show a significant drop in power output. A possible explanation for this decreasing power could lie in the inhibition of some fibers by muscular fatigue which could then reduce the contraction force over the range of motion. It could be further postulated that it is the FT fiber that is being inhibited by fatigue, thus reducing the torque curve and power output.

The classical work by Hill (1938) points out that as a muscle contracts an increase of heat is registered which is proportional to the total shortening. As the fatigue test in this study progressed, additional heat was generated by the heat of shortening, thus producing a further elevation of Tm. If it can be assumed that the high Tm was directly or indirectly responsible for reduction of muscular power, then the tests starting with the higher Tm (W-B and passive heating) would be the first to expect to show the reduction of power. Edwards et al. (1972) found that increasing temperature accelerated glycolysis as measured by increased levels of several glycolytic intermediates. ATP was also found to be lowered at the end of a contraction and the rate of ATP utilization was high. This reduction of intracellular ATP concentrations and the shift to glycolysis to supply ATP could further reduce the muscle's ability to produce force which would then reduce power output.

CHAPTER 5

SUMMARY

Eight male subjects volunteered to participate in a study to determine the relationship between variations in Tm and the characteristics of strength and power development in intact muscle. The subjects were studied under control and four experimental conditions. In the W-A condition, the subject exercised on an isokinetic testing device at 50% ot his peak torque at alever arm speed of 180°/sec, 30 extensions /min for 5 min. The W-B condition was identical to the W-A except the subject exercised an additional 5 min at 60% peak torque immediately following W-A. The remaining two conditions changed Tm passively by 30 min of hot packs or ice packs.

For each of the five conditions, the subject was tested on the Cybex II isokinetic testing device at four lever arm speeds (0, 60, 180 and 300°/ sec), two trials at each speed, followed by a 30 sec fatigue test. Maximal knee extensions at the different lever arm speeds were evaluated for peak torque, 30° torque and time to constant velocity. The fatigue test was evaluated by percent decline and by analysis of the power output at specific time intervals.

The peak torque measurements exhibited a high degree of reliability with correlations of 0.90 or greater for all speeds. The coefficients of variation were found to be small with the highest value being 2.33% for 300°/sec. Tm's were changed an average of +2.9, +4.1, +4.3 and

-14.5°C for W-A, W-B, passive heating and passive cooling respectively. Mean peak torque values, 30° torque values and time to constant velocity values were significantly ($p<.05$) different in the W-A and W-B conditions as compared to the control condition for all lever arm speeds except 300°/sec. Mean 30° torque values for passive heating and cooling were significantly higher than the control condition ($p<.05$) at 60°/sec lever arm speed. Additionally, the mean 30° torque value for passive cooling was significantly lower than the passive heating value ($p<.05$) at 300°/sec lever arm speed. Temperature alteration, passive or active, resulted in no significant change ($p<.05$) in the percent decline as determined from the fatigue test. Evaluation of the power output of the fatigue test indicated that passive cooling significantly ($p<.05$) lowered the power output compared to all other conditions. Interval analysis showed that the W-B and passive heating caused significantly lower power outputs to occur in the second interval when compared to control. Except for the W-B condition, the last three intervals showed significant power reductions ($p<.05$) when compared to control. Additionally, the passive heating condition was significantly lower than the W-B condition ($p<.05$) at the third through the fifth intervals.

It was postulated that the significant changes seen from the active temperature alteration could be the result of (1) a Q_{10} effect on metabolism, (2) an increased ACh release at the neuromuscular end plate, (3) alterations in the action potential, (4) a Q_{10} effect on the contractile characteristics of the ST muscle fibers and (5) a Q_{10} effect on the muscle spindles all combining to improve muscle synchronization.

However, a comparable response to the Q_{10} effect should also have been demonstrated for the passive heating. Therefore, the significant changes found with active warm-up were not a Q_{10} effect, but rather the result of neuromuscular alterations in direct response to actual activity. The significant differences of power output for the fatigue test intervals were thought to be caused by (1) muscle fiber inactivation by cold, (2) muscle fiber inhibition by fatigue and (3) reduction of energy supply.

APPENDIX A

SUBJECT CONSENT FORM

Study Title: The Relationship of Temperature to Strength and Power Development in Intact Human Skeletal Muscle

I understand that my participation in this study is totally voluntary and that I may withdraw from the study at any time without any ill-will on the part of investigator. I further understand that I will participate in the following procedures:

1. PROCEDURE 1 IS FOR PHASE I PARTICIPANTS ONLY.

   I will be participating in four days of testing for Phase I. During this phase I will have the temperature of my thigh changed by two methods. The first will be by hot packs and the second will be by cold packs. I understand that each application or method will be repeated as a measure of reliability.

2. PROCEDURE 2 IS FOR PHASE II PARTICIPANTS ONLY.

   I will be participating in four days of testing for Phase II. During this phase I will have my thigh muscle temperature changed by active work, i.e., leg extension on the Cybex isokinetic device. I realize that I will exercise at two work levels, light and medium, to produce a minimum and maximum muscle temperature respectively. I understand that each change will be repeated as a measure of reliability.

   THE REMAINING PROCEDURES PERTAIN TO ALL PARTICIPANTS.

3. I understand that muscle temperatures will be taken with a needle thermistor probe. I realize that this procedure involves a local anesthesia on the thigh muscle skin followed by an incision of approximately 1/8-1/4 inch in length. The probe will be inserted to depths of 2.5 cm and 5.0 cm below skin surface. All precautions will be taken to insure the sterility of the procedure as well as minimizing the discomfort. I know of no conditions in my medical history which would cause me to think that I cannot participate in this part of the study. I realize that there are risks of blood clotting around the area of the incision and there is also the possibility of infection with any procedure which involves breaking the skin. I also realize that there will probably be some local soreness which may last approximately two days.

4. I will do a series of six leg extensions on each leg on the Cybex isokinetic device at various speeds of limb extension. Each series of extensions will be performed in a maximal manner.

5. I will accomplish a fatigue test which will involve maximal knee extension at 180°/sec on the Cybex isokinetic device. The test will require that I do 25 maximal knee extensions in 30 seconds.

I realize that there will be no costs to me except for the gasoline needed to drive to McKale Center for the laboratory testing. In the event of an accident occurring in the course of the study and directly related to the study, I will assume the cost of any treatment incurred due to this accident.

As a participant in this study I will learn about temperatures effect on strength and power development in muscle and I will learn about temperature affect on fatigue. I realize that this study could be helpful in determining if temperature has any beneficial affects on performance.

I understand that all information concerning my performance during this study will be kept confidential and all data will be filed according to a subject number identification code system. I realize that all procedures will be under the constant and direct supervision of physicians who are involved with the Exercise and Sport Sciences Laboratory in McKale Center.

I have read the above "SUBJECT CONSENT FORM." The nature, demands, risks and benefits of the project have been explained to me. I understand that I may ask questions and that I am free to withdraw from the project at any time without ill will.

I also understand that this consent form will be filed in an area designated by the Human Subjects Committee with access restricted to the principal investigator or authorized representatives of the particular department.

Subject's Signature______________________________Date:____________

Witness's Signature______________________________Date:____________

I have carefully explained to the subject the nature of the above project. I hereby certify that to the best of my knowledge the subject signing this consent form understands clearly the nature, demands, benefits, and risks involved in participating in this study. A medical problem or language or educational barrier has not precluded a clear understanding of his involvement in this project.

____Date:____________
Principal Investigator

APPENDIX B

UNIVERSITY OF ARIZONA, HUMAN SUBJECTS

COMMITTEE APPROVAL LETTER

THE UNIVERSITY OF ARIZONA
TUCSON, ARIZONA 85724
HUMAN SUBJECTS COMMITTEE
ARIZONA HEALTH SCIENCES CENTER 2305
TELEPHONE

December 13, 1978

Mr. Richard W. Cote',III
Department of Physical Education
and Animal Sciences
University of Arizona
Main Campus

Dear Mr. Cote':

The Human Subjects Committee has reviewed your project entitled, "The Relationship of Temperature to Strength and Power Development in Intact Human Skeletal Muscle (HSC #78-104)," and has granted approval of this subjects-at-risk project effective December 13, 1978. Approval is granted with the understanding that no changes will be made in the procedures followed or the consent form used (copies of which we have on file) without the knowledge and approval of the Human Subjects Committee and the Departmental Review Committee. Any physical or psychological harm to any subject must also be reported to each committee.

A university-wide policy requires that all signed consent forms be kept in a permanent file in the Departmental Office to assure their accessibility in the event that university officials need the information and the principal investigator is no longer on the staff or unavailable for some other reason.

Sincerely yours,

Milan Novak

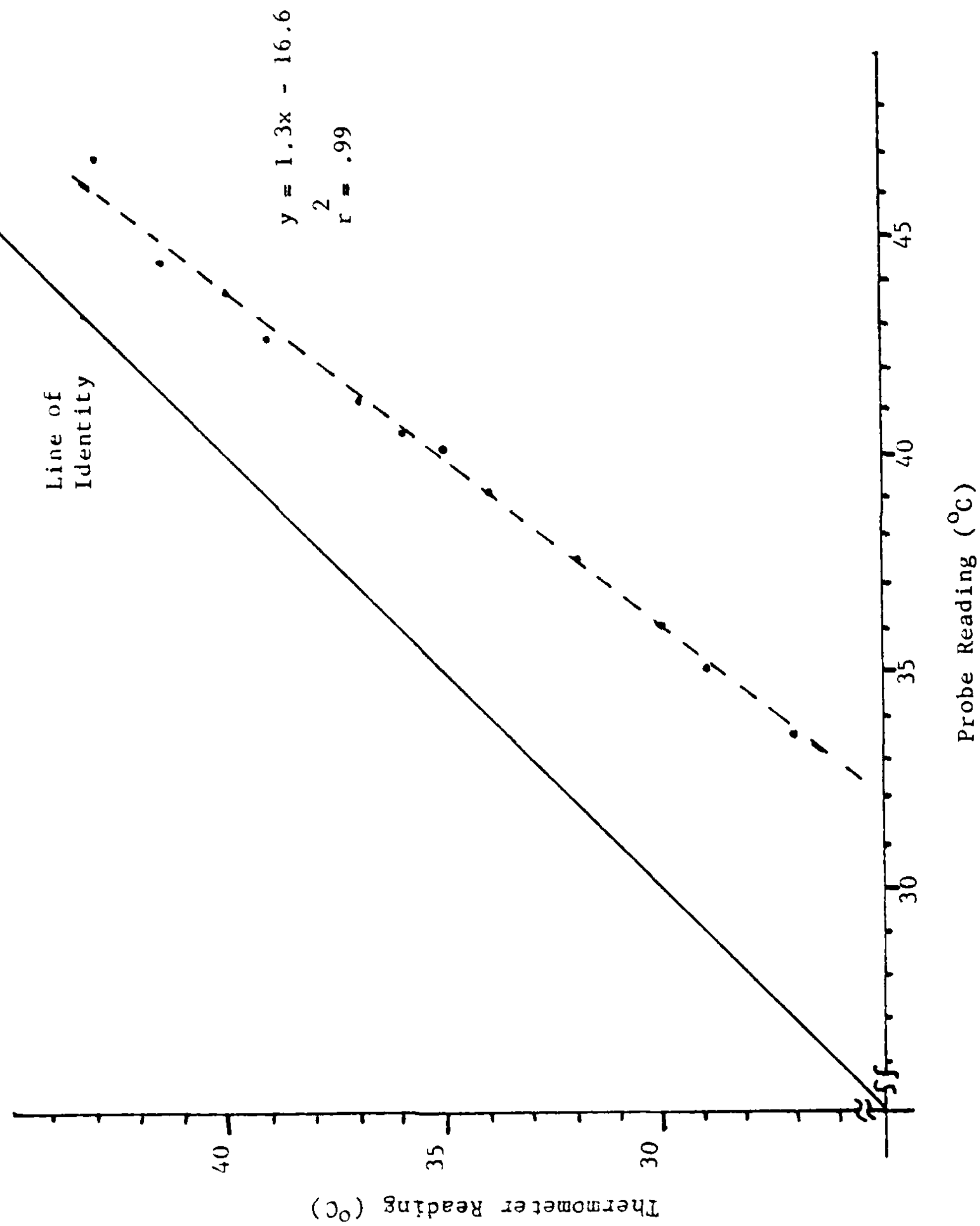
Milan Novak, M.D., Ph.D.
Chairman
Human Subjects Committee

MN:pd

xc: Patricia Fairchild, Ph.D.
Departmental Review Committee

APPENDIX C

CALIBRATION CURVE FOR NEEDLE TEMPERATURE PROBE



Line of Identity
y = 1.3x - 16.6
r^2 = .99
Probe Reading (^oC)
Thermometer Reading (^oC)
30
35
40
45

APPENDIX D

INDIVIDUAL MUSCLE TEMPERATURE (^oC) VALUES

FOR THE PILOT PROJECT

Subject	Day	Trial	Rest	W-A	W-B	Trial	Rest	W-A	W-B
1	1	1	32.78	35.69	36.80	2	32.65	35.89	36.80
	2	1	32.39	36.08	37.12	2	32.33	35.80	37.05
2	1	1	33.48	35.80	36.93	2	33.62	35.80	36.92
	2	1	32.26	36.02	37.05	2	32.13	36.02	37.05
3	1	1	33.18	35.78	36.92	2	33.11	35.89	37.00
	2	1	32.91	35.50	37.00	2	32.85	35.56	36.92
4	1	1	32.91	35.50	37.05	2	32.91	35.56	36.99
	2	1	33.04	35.43	36.86	2	33.04	35.37	36.86

APPENDIX E

INDIVIDUAL MUSCLE TEMPERATURES FOR EACH

SUBJECT AT CONTROL, PASSIVE HEATING

AND PASSIVE COOLING CONDITIONS

Subject	Control	Passive Heating	Control	Passive Cooling
1	33.2	36.6	32.7	18.0
2	32.8	38.1	34.5	21.3
3	33.4	37.6	34.2	26.9
4	34.1	37.7	35.0	16.3
5	33.6	37.1	34.3	21.6
6	33.9	38.3	33.8	16.1
7	31.7	37.7	33.2	16.5
8	33.6	37.8	33.3	18.1

APPENDIX F

INDIVIDUAL PEAK TORQUE VALUES FOR ALL SPEEDS AND UNDER ALL CONDITIONS

Table F1. Individual peak torque values (Nm) for all speeds under control and active warm-up conditions

Speed	0°/sec (isometric)			60°/sec			180°/sec			300° sec		
Subject	Control	W-A	W-B	Control	W-A	W-B	Control	W-A	W-B	Control	W-A	W-B
1	296	324	310	226	232	224	140	153	144	85	96	93
2	232	264	250	170	164	186	108	110	106	70	60	56
3	208	204	212	143	162	162	96	104	92	60	62	64
4	264	316	320	204	212	220	128	132	137	76	88	76
5	252	272	276	180	208	176	100	128	114	72	76	72
6	186	200	200	150	152	168	80	90	90	50	52	52
7	178	183	180	130	144	132	76	80	80	43	47	44
8	320	320	320	216	232	228	126	136	140	80	92	88

Table F2. Individual peak torque values (Nm) for all speeds under control, passive heating and passive cooling conditions

Speed	0^{o}/sec (isometric)			60^{o}/sec			180^{o}/sec			300^{o}/sec		
Subject	Control	Heating	Cooling	Control	Heating	Cooling	Control	Heating	Cooling	Control	Heating	Cooling
1	292	316	336	228	224	272	136	144	134	88	96	80
2	220	228	248	182	172	184	100	108	96	72	70	52
3	188	240	256	146	152	152	96	96	100	84	60	62
4	272	280	256	192	192	164	130	120	112	72	72	58
5	244	212	244	176	176	200	100	100	116	56	68	68
6	194	208	252	142	168	154	84	90	78	44	52	46
7	180	182	166	108	106	84	56	58	58	36	36	38
8	340	332	312	224	216	188	144	144	116	94	70	76

APPENDIX G

INDIVIDUAL 30° TORQUE VALUES FOR ALL SPEEDS UNDER ALL CONDITIONS

Table G1. Individual 30^{o} torque values (Nm) for three speeds under control conditions and under the active modes of warm-up

Speed	60^{o}/sec			180^{o}/sec			300^{o}/sec		
Subject	Control	W-A	W-B	Control	W-A	W-B	Control	W-A	W-B
1	128	148	136	132	144	134	82	94	93
2	96	114	100	92	102	96	70	60	56
3	72	76	74	72	74	76	60	60	64
4	128	134	132	112	122	124	74	88	76
5	84	96	96	96	104	102	70	76	72
6	98	94	96	86	76	80	50	52	52
7	74	83	80	58	70	68	40	44	42
8	96	100	98	116	130	128	80	89	86

Table G2. Individual 30° torque values (Nm) for three speeds under control conditions and under passive heating and cooling conditions

Speed	60°/sec			180°/sec			300°/sec		
Subject	Control	Heating	Cooling	Control	Heating	Cooling	Control	Heating	Cooling
1	168	160	184	128	146	128	84	98	80
2	72	82	92	70	90	88	62	68	52
3	56	58	76	46	56	76	54	60	42
4	120	156	140	122	116	108	68	70	58
5	100	116	118	98	100	112	56	68	68
6	92	98	106	72	74	68	44	48	46
7	52	50	56	42	44	36	34	30	38
8	120	128	124	124	130	110	92	90	76

Table H1. Individual values for time to constant velocity (sec) for three speeds under control and active conditions

Speed	60^{o}/sec			180^{o}/sec			300^{o}/sec		
Subject	Control	W-A	W-B	Control	W-A	W-B	Control	W-A	W-B
1	.03	.03	.03	.05	.04	.05	.07	.06	.06
2	.03	.03	.02	.05	.05	.04	.06	.06	.06
3	.03	.03	.03	.05	.05	.04	.06	.06	.06
4	104	103	103	.04	.04	.04	.06	.06	.06
5	.04	.03	.03	.05	.04	.04	.06	.06	.06
6	.03	.03	.03	.05	.04	.05	.08	.08	.08
7	.04	.03	.03	.05	.04	.04	.08	.07	.09
8	.03	.02	.02	.04	.04	.04	.05	.06	.06

Table H2. Individual values for time to constant velocity (sec) for three speeds under control, passive heating and passive cooling conditions

Speed	60°/sec			180°/sec			300°/sec		
Subject	Control	Heating	Cooling	Control	Heating	Cooling	Control	Heating	Cooling
1	.03	.04	.04	.04	.05	.05	.08	.08	.07
2	.04	.03	.04	.04	.04	.05	.05	.05	.06
3	.04	.04	.04	.04	.05	.04	.06	.06	.07
4	.03	.04	.03	.04	.04	.04	.08	.09	.08
5	.04	.04	.04	.05	.04	.04	.06	.07	.07
6	.03	.03	.04	.05	.05	.05	.08	.08	.09
7	.04	.04	.04	.09	.08	.08	.11	.10	.12
8	.03	.04	.04	.05	.05	.05	.05	.06	.06

APPENDIX I

INDIVIDUAL VALUES FOR PERCENT DECLINE OF THE FIRST THREE TO THE LAST THREE LEG EXTENSIONS DURING THE 30 SECOND FATIGUE TEST

		Active		Passive	
Subject	Control	W-A	W-B	Heating	Cooling
1	33	36	35	32	39
2	19	50	28	35	35
3	20	22	20	23	23
4	33	25	34	28	27
5	21	47	10	16	31
6	32	19	25	29	21
7	32	36	31	38	27
8	45	49	45	46	43

APPENDIX J

INDIVIDUAL VALUES FOR THE SUM OF THE POWER OUTPUT ($Nm \cdot sec^{-1}$) FOR THE FIRST FIVE KNEE EXTENSIONS OF THE 30 SECOND FATIGUE TEST

Table J1. Individual control values for the power output ($Nm \cdot sec^{-1}$) of the five intervals of the fatigue test

	Time Interval				
Subject	6 sec	12 sec	18 sec	24 sec	30 sec
1	344.7	344.7	296.2	310.7	257.3
2	223.3	252.5	237.9	242.7	213.6
3	218.5	218.5	228.2	223.3	228.2
4	315.6	315.6	267.0	218.5	208.8
5	335.0	315.6	305.9	276.8	252.5
6	228.2	213.6	169.9	169.9	165.1
7	169.9	179.6	160.2	121.4	121.4
8	339.9	291.3	262.2	218.5	203.9

Table J2. Individual values for the active conditions for the power output ($Nm \cdot sec^{-1}$) of the five intervals of the fatigue test

	Time Interval W-A					Time Interval W-B				
Subject	6 sec	12 sec	18 sec	24 sec	30 sec	6 sec	12 sec	18 sec	24 sec	30 sec
1	378.7	359.3	237.9	247.6	247.6	364.1	315.6	296.2	242.7	237.9
2	262.2	233.1	194.2	145.7	116.5	276.8	237.9	223.3	218.5	145.7
3	242.8	218.5	218.5	218.5	184.5	242.8	242.8	233.1	203.9	194.2
4	325.3	310.7	271.9	242.7	218.5	315.6	267.0	267.0	233.1	208.8
5	305.9	315.6	301.0	247.6	242.8	335.0	315.6	310.7	286.5	257.3
6	194.2	218.5	184.5	194.2	165.1	242.8	223.3	203.9	189.4	184.5
7	169.9	169.9	150.5	121.4	111.7	160.2	145.7	121.4	121.4	121.4
8	339.9	267.0	257.3	184.5	169.9	335.0	305.9	257.3	218.5	169.9

Table J3. Individual values for the passive conditions for the power output ($Nm \cdot sec^{-1}$) of the five intervals of the fatigue test

	Time Interval - Passive Heating					Time Interval - Passive Cooling				
Subject	6 sec	12 sec	18 sec	24 sec	30 sec	6 sec	12 sec	18 sec	24 sec	30 sec
1	349.6	301.0	267.0	257.3	218.5	373.9	271.9	257.3	242.8	208.8
2	291.3	218.5	242.8	194.2	169.9	291.3	237.9	242.8	160.2	169.9
3	218.5	257.3	208.8	169.9	169.9	252.5	233.1	194.2	169.9	169.9
4	305.9	276.8	271.9	213.6	203.9	262.2	233.1	208.8	213.6	169.9
5	315.6	310.7	267.0	247.6	218.5	291.3	257.3	228.2	242.8	194.2
6	223.3	218.5	169.9	169.9	160.2	179.6	155.4	169.9	160.2	145.7
7	160.2	131.1	131.1	106.8	97.1	111.7	106.8	72.8	72.8	87.4
8	344.7	305.9	267.0	233.1	179.6	276.8	242.8	228.2	194.2	169.9

APPENDIX K

INDIVIDUAL VALUES FOR THE POWER OUTPUT OF THE FIVE INTERVALS OF THE 30 SECOND FATIGUE TEST UNDER ALL CONDITIONS

Subject	Control	Active		Passive	
		W-A	W-B	Heating	Cooling
1	156.3	126.9	145.7	158.2	148.4
2	93.2	122.8	102.8	117.5	114.3
3	78.7	82.4	80.9	93.1	96.6
4	136.6	137.9	145.3	123.1	112.5
5	106.6	109.6	119.4	103.9	116.0
6	93.5	80.0	81.0	66.4	66.8
7	66.6	70.9	67.1	62.9	41.3
8	145.3	133.1	145.3	149.4	112.7

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DAT

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